Finite element analysis of residual stresses in machining

FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES IN MACHINING

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ABSTRACT: Residual stresses play an important role in the service quality of a component. Therefore, it is essential to predict and control residual stresses on the machined surface and subsurface. The paper is focused on the numerical prediction of residual stresses in the orthogonal cutting process of a mild steel. An advanced approach to model heat transfer phenomena at the tool-chip interface was included in the numerical simulation. The FEM results were compared with some experimental data obtained turning AISI 1045 steel using uncoated WC tool.

KEYWORDS: Cutting, Residual Stresses, Heat transfer coefficient, FEM.

1 INTRODUCTION

The machining process provokes a residual stress in the surface layer.
The main causes of residual stresses in machining are: (a) inhomogeneous plastic deformation caused by the mechanical, thermal (frictional) and metallurgical effects, and (b) microstructural transformation associated with the temperature and chip formation process.
The residual stresses on the machining surface are an important factor in determining the performance and fatigue strength of components.
They plays an important role in the service quality of a component. The functional behaviour of machined components can be enhanced or impaired by residual stresses. Therefore, it is essential to predict and control residual stresses on the machined surface and subsurface.
Many research efforts have been made in this direction, including experimental findings, analytical modelling, finite element modelling, and various combinations of those aspects.
Most research on cutting operations has emphasized that cutting parameters [1-7], tool material and geometry [3, 5, 8, 9] and the nature of the worked material [3, 8, 10] heavily influence the development of tensile or compressive residual stresses.
Nevertheless, there are still opportunities for advancing predictive residual stress methods.
The paper is focused on the numerical prediction of residual stresses in the orthogonal cutting process of a mild steel. An advanced approach to model heat transfer phenomena at the tool-chip interface was included in the numerical simulation. The FEM results were compared with some experimental data obtained turning AISI 1045 steel using uncoated WC tool; a good agreement was found out.

2 THERMAL ASPECTS IN MACHINING

Despite FEM codes are nowadays widely utilized, there is still a relevant lack of knowledge which remarkably limits their successful application to the design of cutting processes. The most relevant criticisms involve material characterization for strain, strain rate, material hardness and temperature conditions typical of machining, friction data at the tool/part interface, chip formation and heat transfer conditions.
Obviously these aspects influence the effectiveness of the results provided by finite element simulation, such as residual stresses.
The problem is quite complex because the model must be a coupled thermo-mechanical one. In fact, the residual stresses are generated not only by the material deformation but also by the thermal cycle at which the material is subjected during the cutting process.
According to this, it is clear that prediction of temperature is a key factor and all the aspects related to heat flux have to be carefully taken into account.
Nevertheless, main difficulties are still encountered in temperature modelling of cutting processes.
One of the main problem in temperature modelling, by using the updated-Lagrangian formulation, is that only few milliseconds of cutting time can be simulated, even in the case of 2-D simulations of orthogonal cutting conditions. This very low time is a limit of the modelling, which introduces several problems related to heat generation and diffusion into the tool. In fact, no steady-state conditions are reached during the numerical simulation.
Among the parameters to be set in the numerical simulation, the global heat transfer coefficient at the tool-chip interface (h) plays a relevant role because it directly impacts on the temperature evolution.

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In this paper, an advanced approach to carry out a coupled thermo-mechanical analysis of orthogonal cutting is proposed. First of all, numerical simulation is based on a mixed updated Lagrangian – Eulerian approach. Furthermore, heat transfer at the tool-chip interface is taken into account by means of a global heat transfer coefficient at the tool-chip interface, which is function of the cutting parameters of the process. The details of the entire procedure will be illustrated in the next paragraph.

3 RESIDUAL STRESSES PREDICTION

3.1 EXPERIMENTAL TESTS

The proposed approach was applied to the prediction of the residual stresses in orthogonal cutting.
The validity of the entire procedure was verified by comparing numerical and experimental results taken from literature [11].
In [11] some AISI 1045 steel disks were dry machined orthogonally with uncoated carbide tools, using four different cutting edge radii and three different feeds.
The experimental set-up included a dynamometer for measurement of cutting forces. Table 1 shows the cutting conditions used during the dry orthogonal cutting of AISI 1045 steel. The experiments were repeated three times. The two components of the cutting force, namely the feed (*Ft*) and the cutting forces (*Fc*), were measured using a KISTLER 9121 three-component tool dynamometer.

***Table 1:** Cutting conditions*

Cutting speed [m/min]	175
Feed [mm/rev]	0.05, 0.2
Width of cut [mm]	3
Work material	AISI 1045 steel
Hardness [HB]	200
Disk diameter [mm]	152
Disk thickness [mm]	3
Tool insert type	TNMG-432
Tool material	Uncoated carbide
Tool grade	P20
Tool edge radius [mm]	15, 30, 55, 75

X-ray diffraction method was used to measure residual stress, and this was accomplished by measuring the changes in the distance between crystallographic planes from the unstressed to the deformed condition, i.e., using d-spacing, as a strain gage. Two components of the residual stresses, the axial and the circumferential, were measured on the AISI 1045 steel disk machined surface, but only circumferential stress were taken into account in the numerical procedure.

3.2 NUMERICAL APPROACH

3.2.1 Set-up and verification of the numerical model

As far as numerical simulations are concerned, the SFTC Deform-2D code was utilized. The workpiece was modelled as elastic-plastic, while the tool as rigid. The material behaviour of the AISI 1045 steel was described using the Oxley model [12]. As concerns friction, a simple model based on the constant shear hypothesis ($\tau=m\tau_0$) was implemented, setting m=0.82. The simulation of the thermo-mechanical load was divided in four phases, as depicted in Figure 1.
At first a plane-strain updated-Lagrangian analysis was carried out: no temperature effect was taken into account and the global heat transfer coefficient, *h*, was fixed equal to 0 kW/m^{2}K.

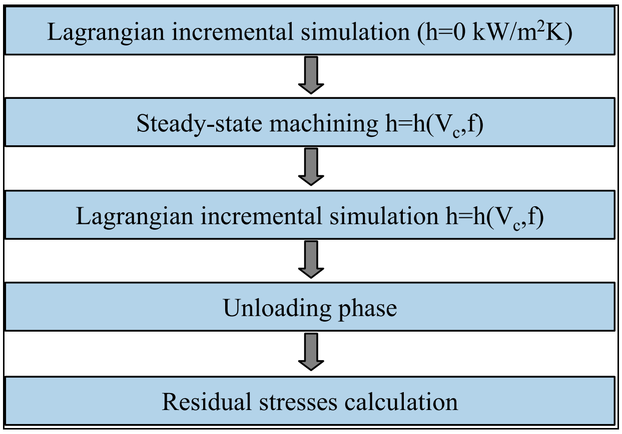

***Figure 1:** Simulation procedure*

When steady-state conditions were reached as concerns cutting forces, chip thickness, shear angle and chip-tool contact length, a coupled thermo-mechanical Eulerian analysis was started based on the outputs of the previous one (geometry, velocities, forces and so on). At this stage, the global heat transfer coefficient at the tool-chip interface, *h*, was assumed as a function of both the normal pressure and the temperature along the contact length [13,14]. In the above mentioned papers, the authors related the coefficient, *h*, also to the cutting parameters (cutting speed, V_c, and feed rate, *f*):

$$h = 442 - 2.36 \cdot V_c - 7950 \cdot f + 0.0276 \cdot V_c^2 + 406000 \cdot f^2 \quad (1)$$

and demonstrated the effectiveness of temperature predictions.
After that, before running the final unloading simulation (which correspond with a cooling simulation too), it was necessary to run an intermediate Lagrangian simulation in order to allow the calculation of the final stress state in the workpiece.
Figures from 2 to 5 show the comparison between experimental and numerical cutting and thrust forces, for a fixed cutting speed (V_c=175 m/min) and for two different feed rates, namely 0.05 and 0.2 mm/rev.

A general acceptable agreement between measured and calculated forces can be observed. In addition the experimental trend at the varying of the tool edge radius is also respected in the numerical predictions.

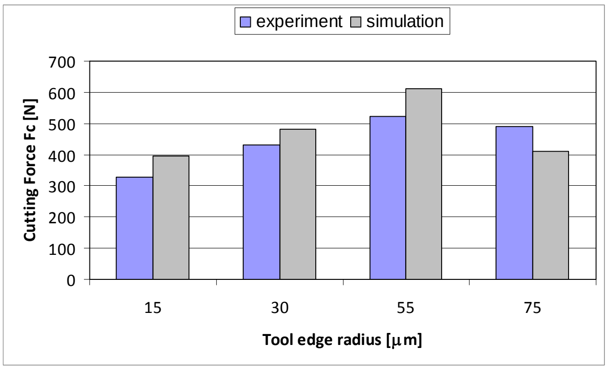

Figure 2: *Experimental and numerical cutting forces for V=175 m/min and f=0.05 mm/rev.*

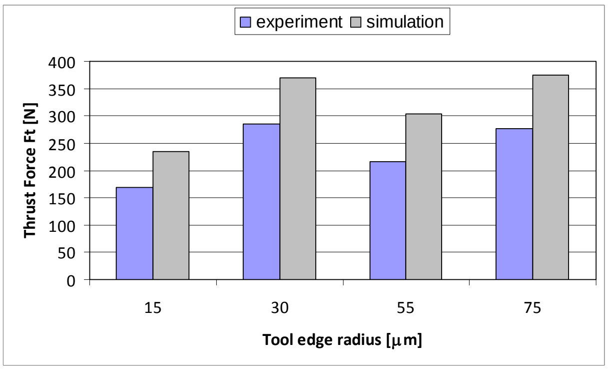

Figure 3: *Experimental and numerical thrust forces for V=175 m/min and f=0.05 mm/rev.*

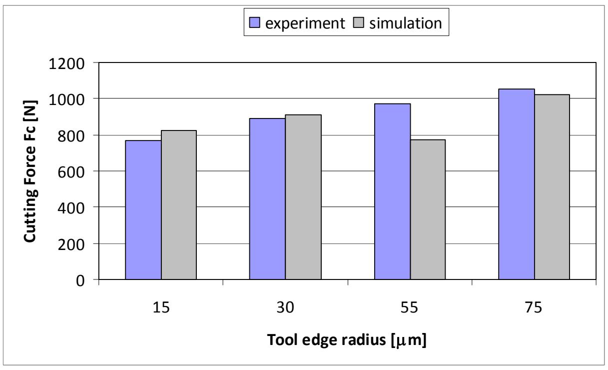

Figure 4: *Experimental and numerical cutting forces for V=175 m/min and f=0.2 mm/rev.*

Finally, since an automatic method for collecting the residual stresses is not yet implemented in SFTC-DEFORM-2D® V.10, the following procedure was employed: (i) For several time steps, the tool was released from the machined surface (unloading phase) and the workpiece was cooled down to the room temperature; (ii) surface and in-depth residual stresses at several locations of the machined surface were collected and the average values were calculated.

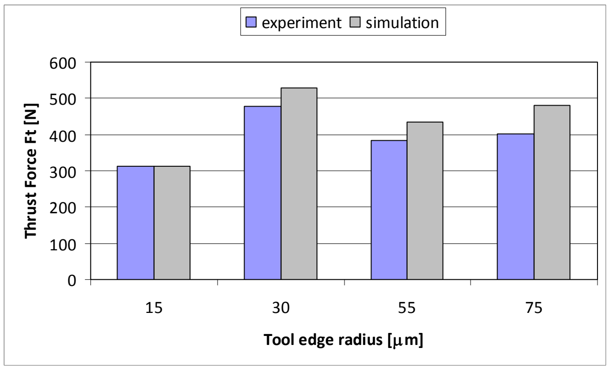

Figure 5: *Experimental and numerical thrust forces for V=175 m/min and f=0.2 mm/rev.*

3.2.2 Numerical results

Figures 6 and 7 show the comparison of predicted surface residual stresses to measured data, at a cutting speed of 175 m/min and for a feed respectively equals to 0.05 mm/rev and to 0.2 mm/rev.

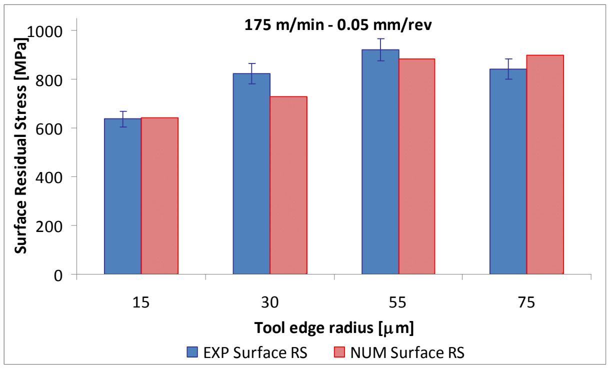

Figure 6: *Experimental and calculated surface residual stresses (V=175 m/min; f=0.05 mm/rev).*

All the values are referred to the circumferential component of the residual stresses. A general good predictive capability of the FEM model can be observed.

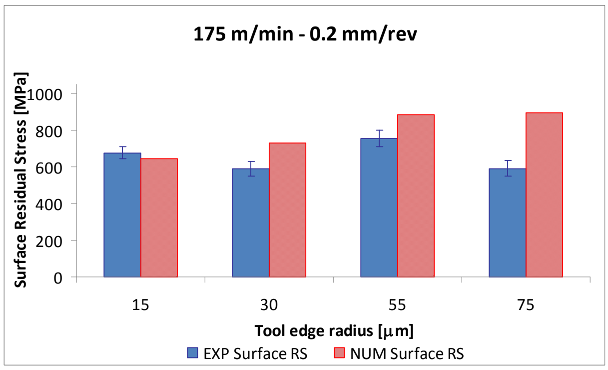

Figure 7: *Experimental and calculated surface residual stresses (V=175 m/min; f=0.2 mm/rev).*

As shown in Figure 7, experimental residual stresses increase with an increase in the edge radius up to a 30 micron edge radius, however there is a decrease in the values of residual stresses for edge radii of 55 and 75 µm.

On the other hand, Figure 6 and Figure 7 illustrate that the predicted residual stresses always increase with the cutting edge radius. This slight difference between measured and predicted trends can be due to the simplification introduced in the numerical model, by using a 2D orthogonal model.

Finally, Figure 8 shows both predicted and measured in-depth circumferential residual stresses for a cutting speed of 175 m/min, an uncut chip thickness of 0.05 mm and a cutting edge radius equal to 55 µm. As depicted in Figure 8, the predicted and measured in-depth residual stress profiles are very well correlated.

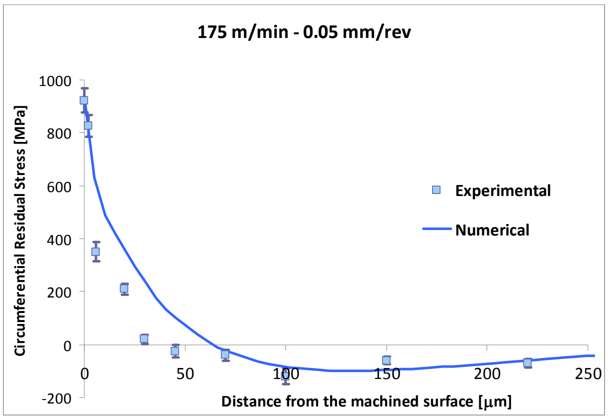

Figure 8: *Experimental and calculated circumferential residual stress profile (V=175 m/min; f=0.05 mm/rev; r=55 µm).*

Moreover, tensile residual stresses were found on the machined surface, while compressive residual stresses can be observed below the surface.

4 CONCLUSIONS

A numerical analysis of residual stresses induced by orthogonal cutting of AISI 1045 was performed in the present investigation. Particularly, it was demonstrated that the reliability of any FE numerical model for predicting the residual stresses is strictly related to the proper prediction of both mechanical and thermal aspects. In this paper all these aspects were carefully taken into account and modelled, permitting to obtain good numerical prediction in terms of superficial as well as in-depth residual stresses. In fact, as illustrated in this research, a reasonable agreement was obtained between the numerical predicted residual stresses and those experimentally measured.

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